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Performance evaluation of power management systems in microbial fuel cell-based energy harvesting applications for driving small electronic devices

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HIGHLIGHTS

► Different power management systems (PMSs) for microbial fuel cells are evaluated.
► Charge pump-capacitor-converter type PMS has a higher power efficiency.
► Capacitor-transformer-converter type PMS has a shorter charging/discharging cycle.

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ABSTRACT

Power management system (PMS) is critical for driving electronic loads using energy harvested by microbial fuel cells (MFCs). Two promising MFC PMS designs, charge pump-capacitor-converter type and capacitor-transformer-converter type, are presented and compared in their performance in driving a wireless sensing system. It is found that the capacitor-transformer-converter type PMS can accommodate lower input voltages, but the charge pump-capacitor-converter type PMS has a slightly higher power efficiency. Furthermore, the charging speed of the capacitor-transformer-converter type PMS is not limited by the charge pump as in the charge pump-capacitor-converter type PMS, resulting in a shorter charging/discharging cycle. The findings suggest that for loads with large duty cycles comparable to the charging time, the charge pump-capacitor-converter type PMS is recommended for its higher power efficiency; on the other hand, for ultra-low MFC output and/or time-sensitive missions, the capacitor-transformer-converter type PMS is recommended for its wider input voltage range and shorter charging/discharging cycle.

1. Introduction

Microbial fuel cells (MFCs), converting chemical energy in organic compounds to electrical energy through catalytic reactions of microorganisms [1–3], have been widely envisioned as one of the sustainable energy harvesting apparatuses. In an MFC, the anode is reduced to a low potential through the oxidation of substrate using microorganisms, generating free electrons, while a high(er) potential is achieved at the cathode through a reduction process. Unfortunately, due to its high internal resistance and low voltage/power output, MFCs are unable to directly drive most commercial electronic devices [4]. The power density of an MFC usually ranges from 1 mW m^{-2} to 2000 mW m^{-2} [5–8]. Various attempts have been made to build larger MFCs [9,10] or connect several MFCs in series—MFC stack operation [11] to increase the power output. However, serial stacking of MFCs has been proved difficult or ineffective [12] to implement in some environments and may lead to even lower outputs due to voltage reversal [11].

Due to its limited power output, MFCs have been utilized to drive low-power electronic devices such as wireless sensor radios. The typical operating voltage of such devices ranges from 2.5 V to 5 V, and the power consumption may be up to the order of 1 W. Unfortunately, depending on its working mode and size, an MFC typically provides a voltage output of 0.3 V–0.9 V and a power output at the order of 10 mW. There is a clear voltage and power gap between those needed by various applications and what MFCs can provide. In order to drive such electronic devices using an MFC, it is possible to use a DC/DC converter to boost the MFC output voltage to a certain required voltage. However, the low output voltage of most MFCs cannot directly drive the DC/DC

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converter. Even if they can, sufficient energy must be stored to power the electronic load after the required voltage is achieved [12]. Therefore, a power management system (PMS) has usually been proposed to interface the MFC with the electronic load by accumulating MFC energy first and then driving the load intermittently.

Various PMSs have been proposed to drive electronic loads using different MFCs [4,10,12–15], and each PMS design has its own application characteristics. However, no study to date has systematically compared the different PMSs' suitability for practical applications. The objective of this study is to evaluate the performance of two common types of PMSs in MFC energy harvesting applications for driving small electronic devices. The comparison study is organized as follows. First, available PMSs for MFC energy harvesting are reviewed. Second, the setup of PMS performance evaluation systems and the evaluation metrics are introduced. Then, experimental evaluation results are presented and discussed, followed by some PMS application notes. Finally, the paper concludes with some future work envisioned.

2. Background

PMS, an electronic system aiming to regulate voltage or power per application needs, is widely implemented in various energy harvesting systems with a low-voltage/power output. An ideal PMS should be able to boost its low input voltage to a high output voltage and provide enough power in bursts to drive typical commercial electronic devices intermittently. As such, a PMS usually utilizes a DC/DC converter to boost voltage and includes a super-capacitor as a temporary energy storage device to accumulate energy from a low-power energy source. Super-capacitors are commonly adopted due to the long lifetime and the ability to output high-current within a short period of time [12–15].

Currently, PMSs have been applied with four types of energy harvesting systems: solar cells [16,17], thermoelectric generators [18,19], fuel cells [12,13,20,21], and piezoelectric generators [22,23]. All PMSs have a similar circuit design for energy harvesting systems with a positive voltage output except those for piezoelectric generators. Piezoelectric generators are AC voltage sources that require an external bridge rectifier to regulate their voltage and current polarities [24].

Different PMS variants for MFCs have been studied for intermittent driving of electronic loads. The simplest PMS implementation is to directly connect a super-capacitor to an MFC to increase and control the electrical potential generated by the MFC [13,14] as schematically shown in Fig. 1(a). While it may work, the achievable voltage of super-capacitor is unfortunately limited by the MFC output voltage, which is usually very low (normally, lower than 0.8 V), meaning that only limited energy can be stored and utilized per charging/discharging cycle.

To overcome this shortcoming of limited energy storage, a charge pump has been proposed to boost the input voltage for the super-capacitor [12] as shown in Fig. 1(b), and there is no direct connection between an MFC and the super-capacitor. Such a PMS works with low-voltage outputs from MFCs; however, it should be pointed out that it only works well if the MFC output voltage is high enough to drive a charge pump, and the system charging/discharging cycle might be long since the charging speed is limited by the charge pump. To further lower the PMS input voltage without sacrificing the charging speed, a transformer has been introduced in a capacitor-transformer-converter PMS design [4] as shown in Fig. 1(c), with one super-capacitor ($C_{transformer}$) to drive the following DC/DC converter and the other (C_0) to drive load in bursts with high voltage and power. This PMS works well when the MFC output voltage is as low as 0.18 V [4].

The characteristics of the aforementioned three PMS designs are summarized in Table 1. No study to date has evaluated and compared the applicability of different PMSs in practical applications. This study conducts a systematic comparison of the two advanced PMS designs: charge pump-capacitor-converter type and capacitor-transformer-converter type to achieve better understanding of their MFC-related application feasibility.

3. Performance evaluation of power management systems

To evaluate the application feasibility of charge pump-capacitor-converter and capacitor-transformer-converter PMSs, two evaluation systems were set up, respectively, and their performance was evaluated in three key metrics: PMS input voltage, PMS charging/discharging cycle time, and PMS power efficiency.

3.1. Evaluation systems setup

The performance evaluation systems consisted of three main components: an MFC, a PMS and an electronic load which was a wireless sensing and transmitting system.

3.1.1. MFC

A single-chamber air-cathode MFC reactor was constructed based on the same setup as used in Ref. [4]. The reactor had an anodic chamber volume of 316 ml, and the anode was made of 0.381 mm thick carbon cloth (CCP30CM, Fuel Cell Earth, Stoneham, MA, USA). The cathode was made of 0.28 mm thick carbon paper (TGP-H-090, Fuel Cell Earth, Stoneham, MA, USA), which was covered with Pt-catalyst (XC-72, Fuel Cell Store, Boulder, CO, USA). The electrodes, apart by 2.5 cm and separated by a 0.18 mm thick Nafion membrane (N117, DuPont, Wilmington, DE, USA), each had a diameter of 12.7 cm. A stainless mesh was attached to the outside of the cathode to prevent possible cathode deformation during operation. Anaerobic domestic wastewater was used as both the

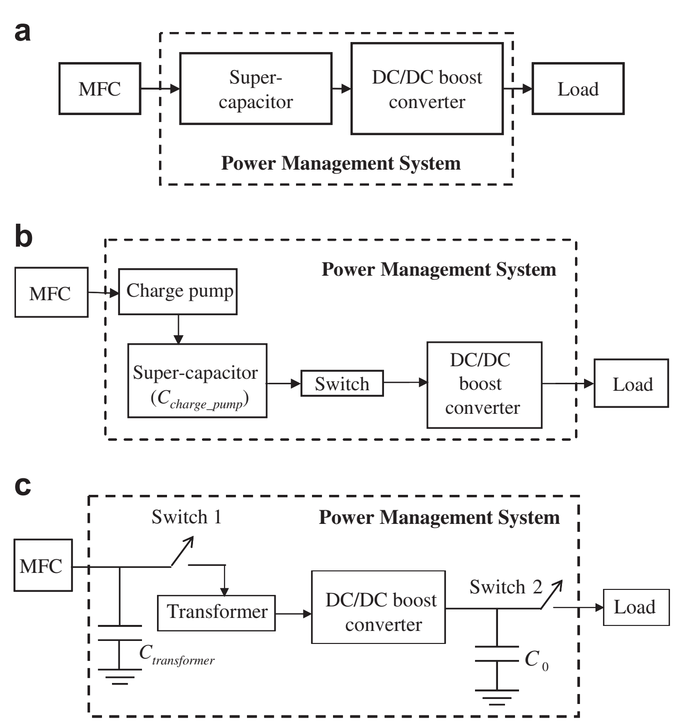

Fig. 1. Schematics of different MFC PMSs: (a) capacitor-converter type, (b) charge pump-capacitor-converter type, and (c) capacitor-transformer-converter type.

Table 1
Characteristics of main MFC PMS designs.

PMS design	Location of super-capacitor(s)	Advantages	Disadvantages
Capacitor-converter type [13,14]	One super-capacitor which is directly connected with an MFC.	Simple setup	It cannot drive the DC/DC converter if the open-circuit-voltage (OCV) is lower than the required input voltage of the converter.
Charge pump-capacitor-converter type [12,15]	One super-capacitor which is connected between the charge pump and the DC/DC converter.	Higher discharging voltage of the super-capacitor	It cannot charge the super-capacitor if the MFC output is lower than the required input voltage of the charge pump.
Capacitor-transformer-converter type [4]	Two super-capacitors: one is directly connected with an MFC and the other is connected between the DC/DC converter and the load.	Lower PMS input voltage	Additional super-capacitor is needed after the converter to improve the load driving performance.

inoculum and the substrate during the inoculation process with some additional nutrient medium as described in Ref. [4]. After inoculation, the inoculation solution was replaced with deoxygenated wastewater supernatant.

3.1.2. PMS designs

The charge pump-capacitor-converter type PMS consists of a charge pump (S-882Z, Seiko Instrument, Japan), a super-capacitor (C_{charge_pump}), a DC/DC boost converter (L6920DB, ST Microelectronics, Geneva, Switzerland) and solid state switches (SI3460BDV, SI3499DV, Vishay Americas, USA). The charge pump draws a low current from the MFC and charges the super-capacitor. When the voltage of the super-capacitor is lower than the discharging voltage [12], the switch is open and thus the boost converter is disconnected from the super-capacitor. Once the super-capacitor voltage reaches the discharging voltage, the switch is closed and connects the DC/DC converter with the super-capacitor. Then the DC/DC converter supplies a 3.3 V voltage output to the load per its specification [25]. The discharging voltage used in this study was 1.8 V [12,25].

The capacitor-transformer-converter type PMS consists of a LTC3108 voltage step-up converter (Linear Technology, Milpitas, CA, USA) [26]. The first super-capacitor ($C_{transformer}$) is charged by the low-voltage output of MFC. Switch 1, comprising of a Germanium transistor and an ALD110800 MOSFET (Advanced Linear Device, Sunnyvale, CA), is utilized to prevent the transformer and LTC3108 drawing current from the first super-capacitor while it is being charged. Once the voltage of the super-capacitor reaches the discharging voltage (0.41 V) specified by the hardware, Switch 1 closes and the first super-capacitor works as the power source to drive the rest of the PMS as well as the load. The voltage of the first super-capacitor is then amplified by the transformer (LPR6235-752SML, Coilcraft, Cary, IL, USA), and the amplified voltage is rectified by an internal rectifier circuit. While the first super-capacitor discharges, the second super-capacitor (C_0) starts being charged. Once the voltage of the first super-capacitor drops below the charging voltage (0.18 V), Switch 1 opens and the first super-capacitor begins being charged again. This process iterates for a few times until the voltage of the second super-capacitor reaches the required load voltage (such as 3.3 V for typical wireless sensors), when Switch 2 (2N3904, ST Microelectronics, Geneva, Switzerland) closes to power the load. The function of Switch 2 is to connect the load when the second super-capacitor is fully charged and to prevent the load from drawing current when the second super-capacitor is being charged.

This study adopts commercially available DC/DC converters for both PMS types while focusing on the performance dependence on the choice of super-capacitor values. Specifically, the average output power drawn from an MFC is of interest. The optimal capacitance is defined as the one that achieves the highest average output power. When the super-capacitor starts to draw energy from an MFC, the voltage increases gradually until it reaches the discharging voltage (V_d), at which the super-capacitor starts discharging to the rest of the PMS and the load until the voltage on the super-capacitor drops to the charging voltage (V_c). As such, the average output power during a single PMS charging cycle can be calculated as follows [27]:

$$P_a = \frac{1}{2T_c}C_{storage}\left(V_d^2 - V_c^2\right) \tag{1}$$

where T_c is the charging time for the super-capacitor to be charged from V_c to V_d and $C_{storage}$ is the super-capacitor capacitance. In this study, T_c was measured. It should be noted that T_c can also be predicted based on the MFC equivalent circuit as described in Ref. [4]. The selection of optimal capacitance is slightly different for the two PMS types as discussed in the following.

3.1.2.1. Optimal capacitance for charge pump-capacitor-converter type PMS. There is only one super-capacitor (C_{charge_pump}) in the charge pump-capacitor-converter type PMS. The energy stored in the super-capacitor can be related to the energy harvested from an MFC as follows:

$$\frac{1}{2}C_{storage}\left(V_d^2 - V_c^2\right) = \eta_c U_{in} I_{in} T_c \tag{2}$$

where η_c is the efficiency of the charge pump, and U_{in} and I_{in} are the charge pump input voltage and input current, respectively. U_{in}, I_{in} and T_c were experimentally measured. Based on Eqs. (1) and (2), the generated average power of the charge pump-capacitor-converter type PMS can be obtained:

$$P_a = \frac{1}{2T_c}C_{storage}\left(V_d^2 - V_c^2\right) = \eta_c U_{in} I_{in} \tag{3}$$

As η_c, U_{in} and I_{in} usually don't vary too much for a given MFC and charge pump, the average power generated is almost fixed. As such, there is no optimal capacitance for the charge pump-capacitor-converter type PMS, and the value of super-capacitor only needs to be selected such that P_a satisfies the minimum power requirement of load. The selected capacitance was 0.25 F in this study.

3.1.2.2. Optimal capacitance for capacitor-transformer-converter type PMS. Two super-capacitors ($C_{transformer}$ and C_0) are used in the capacitor-transformer-converter type PMS. While the second super-capacitor (C_0) is directly determined based on the power need of loads, the first super-capacitor $C_{transformer}$ should be

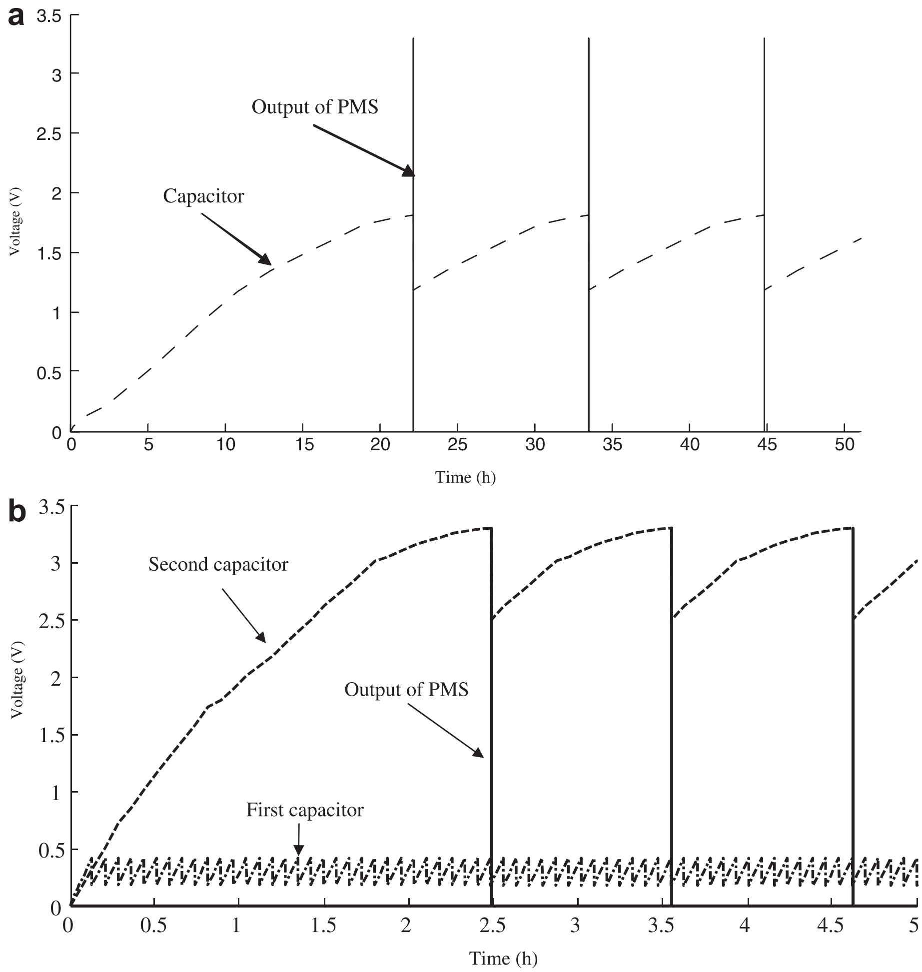

Fig. 2. Super-capacitor voltages and the PMS output voltages when using (a) charge pump-capacitor-converter type PMS and (b) capacitor-transformer-converter type PMS.

optimized to maximize P_a. Optimal $C_{transformer}$ value was determined using an experimental approach [4]. Different super-capacitors were connected to the MFC to be charged first. Once the voltage on the super-capacitor was charged from V_c to V_d, the charging time T_c was recorded. The average output power P_a during a single charging cycle was then calculated based on Eq. (1). The optimal capacitance is the one which achieves the maximum average power; the optimal capacitance in this system setup was 1.5 F.

3.1.3. *Electronic load*

In this study, the energy harvested from the MFC was used to power the MDA300 sensor board [28] and MICAz wireless sensor node (Moog Crossbow, Milpitas, CA, USA) [29]. An MDA300 is embedded with humidity and temperature sensors, while a MICAz can be used to transmit sensing data collected by the MDA300. The MICAz node features a Chipcon CC2420 IEEE 802.15.4-compliant radio chip, supporting a fixed 250 kbps data rate, controllable transmit power from −25 dBm to 0 dBm, and 16 selectable channels in the 2.4 GHz band. Channel 26 (2478.5–2481.5 MHz) was used for the experiments. The voltage requirement is 3.3 V, and the power consumption is around 65 mW for radio transmission with a 0 dBm transmission power and 30 mW for MDA300 sensing. The PMS stores the MFC harvested energy and converts it to a high-voltage output driving the wireless sensor node intermittently whenever enough energy is accumulated in the super-capacitor.

3.2. *Evaluation metrics*

3.2.1. *PMS input voltage*

The PMS input voltage is the minimum MFC output voltage required to drive a PMS.

3.2.2. *PMS charging/discharging cycle time*

The PMS output voltage is the open circuit voltage measured at the PMS output side and usually regulated at certain standard levels to drive electronic devices. Generally speaking, PMS begins its charging process after the voltage of super-capacitor(s) falls below the charging voltage. The charging process is completed once the discharging voltage is reached, and PMS starts discharging and powering the load. Herein the PMS charging/discharging cycle time is defined as the time interval between two consecutive charging processes.

3.2.3. *PMS power efficiency*

The PMS efficiency is an indicator of how much power or energy is transferred from an MFC to a load, and it is usually defined based on the ratio of the PMS output power over the PMS input power (of a DC/DC converter) [14]. Since the MFC output power may be affected by the PMS and varies during each charging and discharging cycle, it may result in a varying input power to a PMS. As such, the power efficiency herein is determined as the ratio of the average PMS output power (P_{out}) over the average PMS input power (P_{in}) for a complete charging and discharging cycle [30] as follows:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (4)$$

For determining the power efficiency, the time-variant input voltage, input current, output voltage and output current can be recorded by multimeters.

4. Experimental results and discussion

4.1. PMS input voltage

For the charge pump-capacitor-converter type PMS, the input voltage is determined by the specification of the selected charge pump which was 0.3 V per the Seiko charge pump used in this study [25]. For the capacitor-transformer-converter type PMS, the input voltage is determined by the voltage needed to drive the transformer; in this study, it was measured as 0.18 V per the selected MOSFET.

4.2. PMS charging/discharging cycle time and discussion

4.2.1. PMS charging/discharging cycle time

Both the PMSs were charged by the MFC and then used to drive the wireless sensor node to transmit five packets each time: three humidity and temperature packets and two control packets. The charging/discharging cycle time for each PMS was measured. Fig. 2 shows the super-capacitor voltages and the PMS output voltages.

For the charge pump-capacitor-converter type PMS, a 0.25 F super-capacitor was used to drive the wireless sensing system. When the voltage on the super-capacitor reached 1.8 V, the internal switch of charge pump closed and the super-capacitor began to discharge and drive the load. The DC/DC converter output a voltage of 3.3 V to drive the wireless transmitter. When the voltage on the super-capacitor decreased to 1.2 V, the switch of charge pump opened and the super-capacitor started charging again. It took about 22 h (the start-up phase) to charge the super-capacitor from 0 V to 1.8 V using the charge pump and 11.3 h (the steady-state phase) from 1.2 V to 1.8 V.

For the capacitor-transformer-converter type PMS, the first super-capacitor, which was selected as the optimal capacitance (1.5 F), was charged to 0.41 V and discharged to 0.18 V. The average capacitor charging time was measured about 273($\pm$5) s (Fig. 2(b)). The second super-capacitor was selected as 54.2 mF in order to transmit five packets once fully charged. When the first super-capacitor was charged to 0.41 V, Switch 1 closed and began to charge the second super-capacitor. It took about 2.5 h to charge the 54.2 mF super-capacitor from 0 V to 3.3 V. Then Switch 2 closed and started driving the wireless sensing node. When the voltage of the second super-capacitor decreased to 2.5 V, Switch 2 opened and the second super-capacitor was then charged again. It took about 1.06 h to charge the second super-capacitor from 2.5 V to 3.3 V.

Fig. 3 shows representative samples of transmitted humidity and temperature data acquired at the Clemson Advanced Manufacturing & Systems Integration Laboratory, Clemson University, Clemson, SC, USA. As seen from Fig. 3, the time between transmissions is 11.3 h when using the charge pump-capacitor-converter type PMS while 1.06 h when using the capacitor-transformer-converter type PMS. Since the laboratory humidity and temperature did not vary too much during each packet transmission cycle, only one humidity and temperature reading was shown each time.

4.2.2. Discussion on PMS charging/discharging cycle time

The dependence of charging time on the capacitance is further studied by using a wide range of applicable capacitances for the capacitor-transformer-converter type PMS (50, 54.2, 83.3, 100, 200, 300, and 400 mF) and the charge pump-capacitor-converter PMS (200, 250, 300, and 500 mF). It should be noted that only a 50 mF second super-capacitor was needed if three packets were to be transmitted when using the capacitor-transformer-converter type PMS. The charging time and capacitance relationship is shown in Fig. 4(a), and as discussed before, the capacitor-transformer-converter type PMS has a shorter charging/discharging cycle. A high capacitance super-capacitor also results in more transmitted packets (Fig. 4(b)) for each type PMS. It can be seen that both the charging time and number of transmitted packets increase linearly with the capacitance.

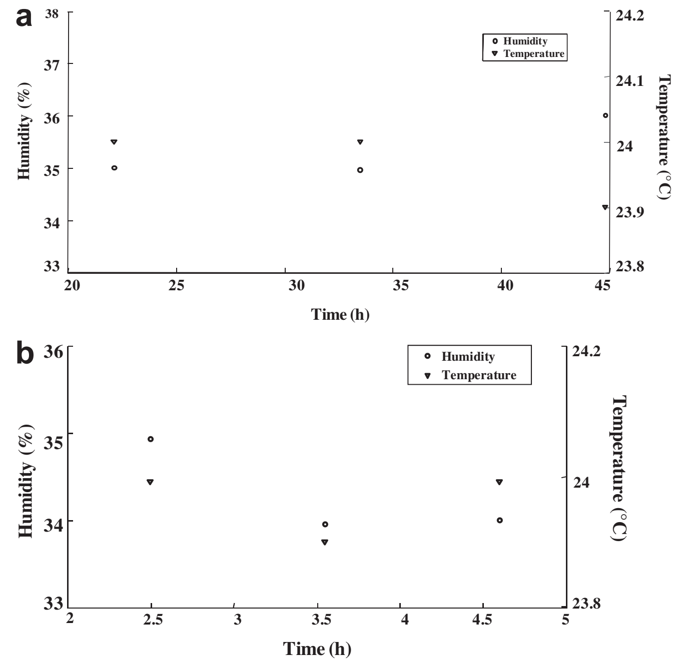

Fig. 3. Sensor data acquired and transmitted using: (a) charge pump-capacitor-converter type PMS and (b) capacitor-transformer-converter type PMS.

More importantly, the capacitor-transformer-converter type PMS is able to send more packets than that of the charge pump-capacitor-converter type PMS for a given charging time as seen from Fig. 5, suggesting the benefit of using the capacitor-transformer-converter type PMS. This performance difference is because the charge pump used in the charge pump-capacitor-converter type PMS limits the input current to the PMS, meaning that the energy harvested is less than that harvested using the capacitor-transformer-converter type PMS for a given period.

4.3. PMS power efficiency

For the charge pump-capacitor-converter type PMS, the charge pump is utilized to draw power from the MFC, boost the voltage to 1.8 V and store the energy in the super-capacitor. Once the voltage of super-capacitor reaches 1.8 V, it starts driving the DC/DC converter to output 3.3 V. The power efficiency was measured as the ratio between the input power to the charge pump and the output power from the DC/DC converter, and it was 5.33%.

For the capacitor-transformer-converter type PMS, the power efficiency was measured as the ratio between the input power to the first super-capacitor (1.5 F) and the output power from the second super-capacitor (0.05 F). The power efficiency was 4.29%, lower than that of the charge pump-capacitor-converter type PMS.

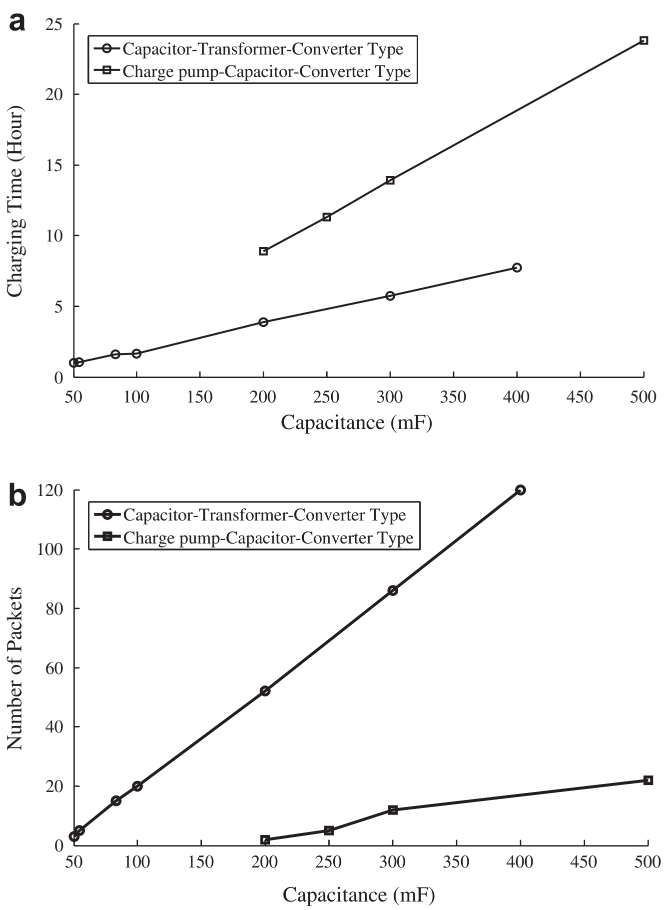

Fig. 4. PMS performance at different capacitances: (a) charging time vs. capacitance and (b) number of transmitted packets vs. capacitance.

It is recognized that there is an additional super-capacitor after the LTC3108 DC/DC converter, which reduces the power efficiency.

It should be noted that overall both the PMSs have a low power efficiency due to the charge pump or the transformer, respectively, in addition to the super-capacitor(s) and DC/DC converters adopted in the circuits. Both the charge pump and the transformer convert a low DC voltage to another by storing the input energy temporarily and then releasing that energy at a different voltage. The storage may be in either electric field storage components (charge pump) or magnetic field storage components (transformer). There always is energy loss associated with the voltage conversion process. Particularly, for the capacitor-transformer-converter type PMS, the transformer-related energy loss originates from the current flow in the transformer windings in forms of the resistance loss and eddy loss [31]. While the resistance loss is usually not pronounced, the eddy loss, which is proportional to the current frequency, can be high because a high conversion ratio usually comes with a high current frequency [32]. Regardless the types of PMS, how to improve the PMS power efficiency with a high driving capability and conversion ratio remains an open challenge for PMS circuit designs.

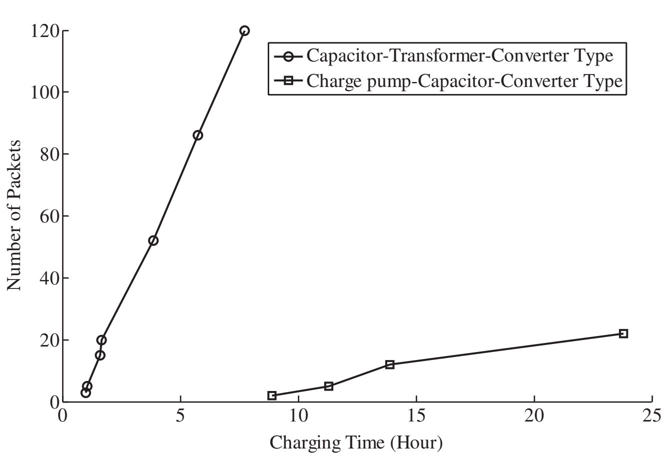

Fig. 5. Number of transmitted packets as a function of charging time.

Some much higher power efficiencies have been reported for various MFC PMSs [10,12,14,33–35]. The differences between their power efficiencies and that reported in this study are due to different power efficiency definitions adopted. For example, Tender *et al.* [10] reported an 85% efficiency without considering the super-capacitor in their estimation; Donovan *et al.* [14] estimated their power efficiency (75%) based on the ratio of the power output after the DC/DC converter to the power input after the super-capacitor; Park and Ren [34,35] reported a more than 70% efficiency for the P-ch MOSFET based synchronous boost converter without including the possible loss due to the secondary output voltage boost converter and the additional control circuit. Some other studies reported power efficiency values only for individual PMS components such as charge pumps and DC/DC converters [12,33] without mentioning the overall power efficiency for the whole PMS. For confirmation, the power efficiency estimated in this study for the charge pump-capacitor-converter PMS has been shown to have a comparable efficiency as that reported in Refs. [12] and [14] if the power efficiency is estimated using the same methodology. For sediment-type MFCs that are usually applied to power sensors and have less concern about energy loss, a simple PMS as discussed in this study will be sufficient. In applications requiring a higher power efficiency with reactor MFCs and even some sediment-type MFCs, different PMS designs are needed.

5. Notes of PMS selection

The discussed charge pump-capacitor-converter type and capacitor-transformer-converter type PMSs share some similarities: 1) having simple super-capacitor-based circuits; and 2) being able to boost a low MFC output voltage to 3.3 V. However, there are some distinct performance differences between these two PMSs. Table 2 summarizes their differences. Some key points are listed as follows:

1. Capacitor-transformer-converter type PMS can accommodate lower input voltages depending on the design of Switch 1;

Table 2
Key differences between two PMSs in this study.

	Charge pump-capacitor-converter PMS	Capacitor-transformer-converter PMS
Minimum acceptable input voltage (V)	0.3	0.18
Power efficiency	5.33%	4.29%
Capacitance selection	Capacitance is selected based on the need of load.	The first super-capacitor is optimized to achieve a maximized MFC power output while the second super-capacitor is selected based on the need of load.
Charging time needed to transmit 5 packets	11.3 h	1.06 h

2. Charge pump-capacitor-converter type PMS has a slightly higher power efficiency;
3. The charging speed of the capacitor-transformer-converter type PMS is not limited by the charge pump as in the charge pump-capacitor-converter type PMS, resulting in a shorter charging/discharging cycle. This means that the capacitor-transformer-converter type PMS is more capable in harvesting more energy from an MFC even the charge pump-capacitor-converter type PMS has a higher power efficiency. The charge pump-capacitor-converter type PMS may not be able to utilize all energy produced by an MFC depending on the charge pump selected.

Furthermore, some PMS application notes are summarized as follows:

1. If loads have large duty cycles comparable to the charging time, the charge pump-capacitor-converter type PMS is recommended for its higher power efficiency; and
2. If the MFC-based system is for ultra-low MFC output and/or time-sensitive missions, the capacitor-transformer-converter type PMS is recommended for its wider range of input voltage and shorter charging/discharging cycle.

6. Conclusions and future work

PMSs are designed to accumulate energy from MFCs and boost the low input MFC voltage to a high output voltage to drive various electronic loads. Two promising MFC PMS designs, charge pump-capacitor-converter type and capacitor-transformer-converter type, are presented and compared in terms of their use performance. Some conclusions are drawn as follows:

1. The capacitor-transformer-converter type PMS can accommodate lower input voltages, but the charge pump-capacitor-converter type PMS has a slightly higher power efficiency; and
2. The charging speed of the capacitor-transformer-converter type PMS is not limited by the charge pump as the charge pump-capacitor-converter type PMS, resulting in a shorter charging/discharging cycle.

If loads have large duty cycles comparable to the charging time, charge pump-capacitor-converter type PMS is recommended for its higher power efficiency. If the MFC-based system is for ultra-low MFC output and/or time-sensitive missions, the capacitor-transformer-converter type PMS is recommended. Future work should focus on the design of high power efficiency PMSs and the selection of high efficiency electronic components for PMS implementation. At the same time, future work should identify the most suitable MFC for respective applications. This current work used a widely studied single-chamber MFC with wastewater inoculum for convenience. For monitoring outdoor environmental conditions, for example, a sediment MFC which uses indigenous bacteria and works in outdoor environments would be more suitable.

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